Agenzia Spaziale Italiana

The Compton Spectrometer and Imager - COSI

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www.asi.it

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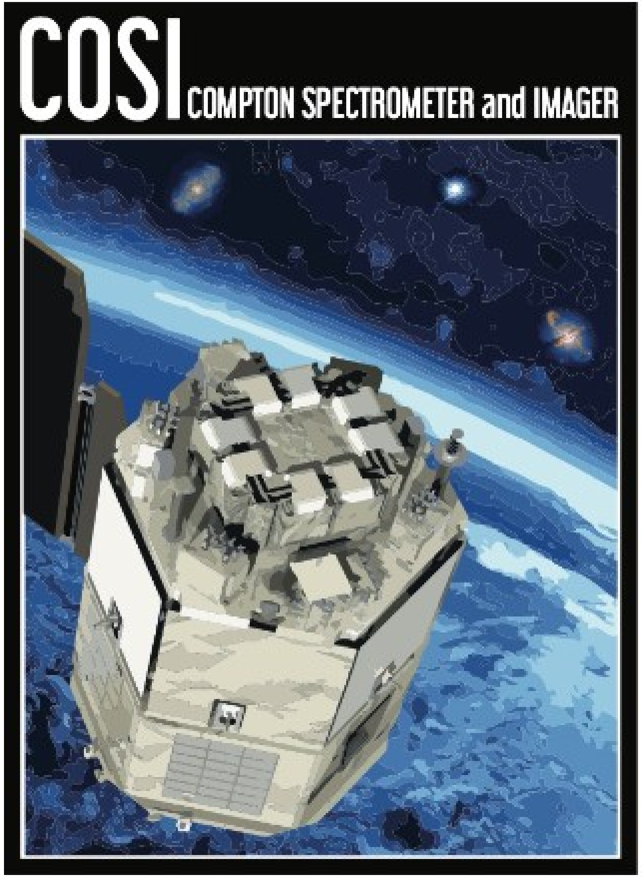
Introduction



The scientific objectives of the Compton Spectrometer and Imager

The Compton technique

The COSI mission

The COSI detector

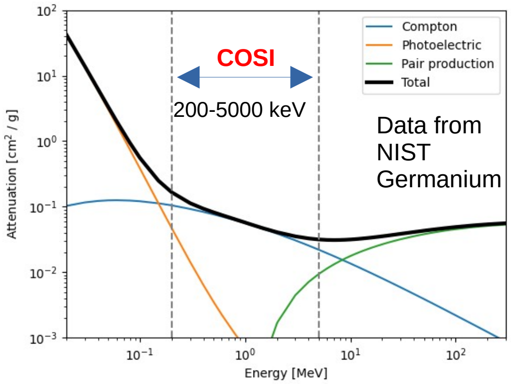
The COSI scientific requirements and expected performance

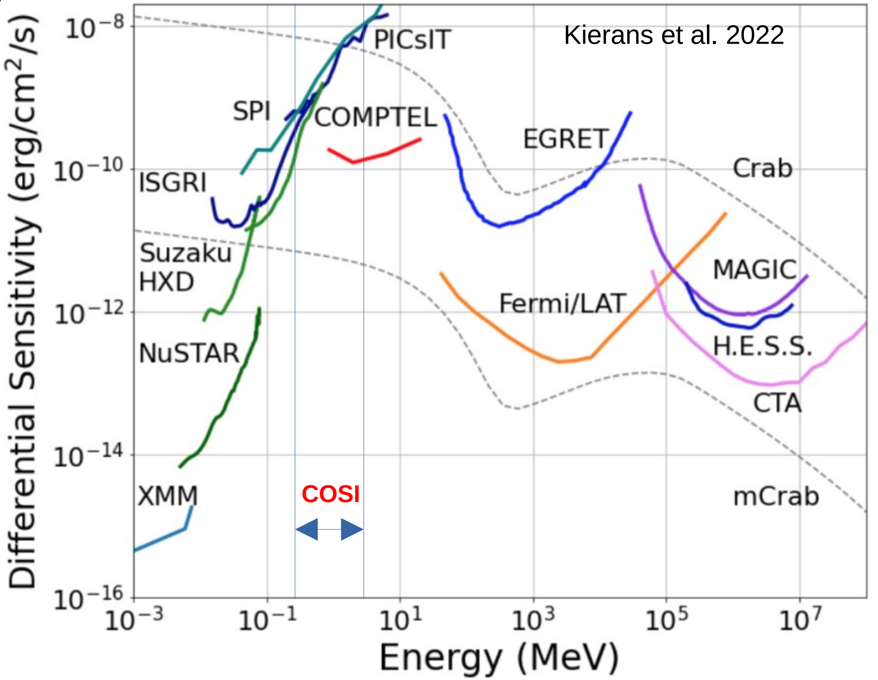
The current experimental status

Main challenges of Compton telescopes

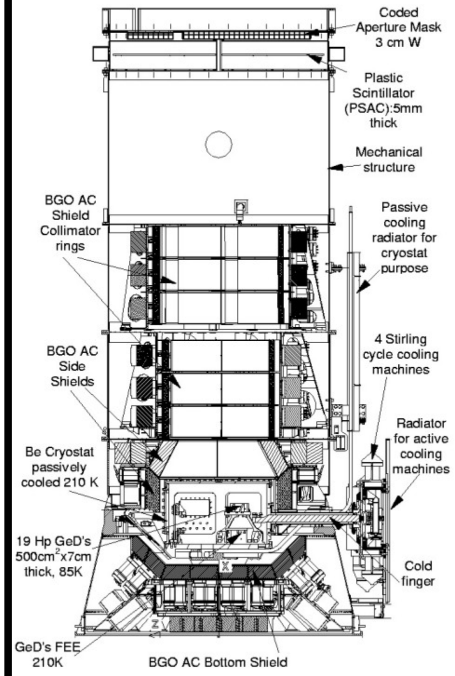
- ~20 g/cm^2 mean interaction length @1MeV
- Multiple scatterings for each event
- Background rejection is difficult
- Photon direction reconstruction is difficult

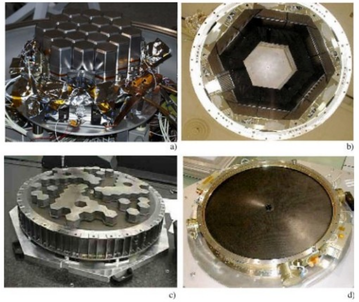
One of the least explored regions around ~MeV (so-called "MeV gap")





INTEGRAL-SPI and COMPTEL (the present status)



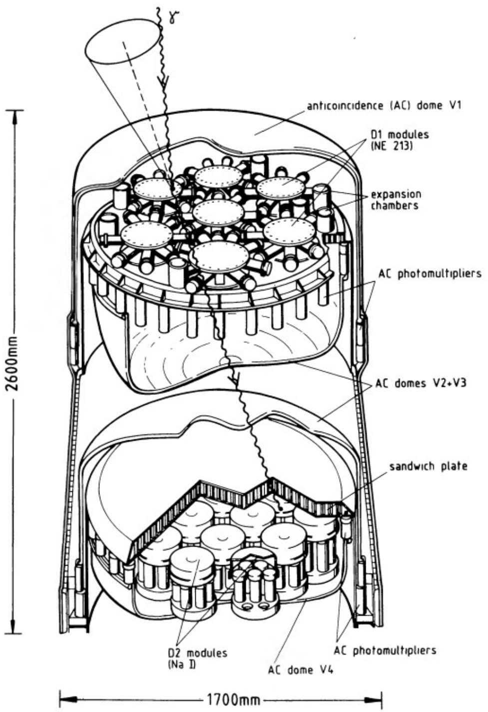


Vedrenne et al. 2003

INTEGRAL-SPI
Tungsten coded mask

19 Germanium detectors at 85 K

20 keV – 8MeV
16°x16° FOV



Schoenfelder et al. 1993

COMPTEL
2 planes detector
- Top: liquid scintillator
- Bottom: NaI(Tl) scintillator

Bottom:
- Energy

Top & Bottom:
- Direction
- Time-of-flight

1 – 30 MeV
1 sr FOV

The positron annihilation

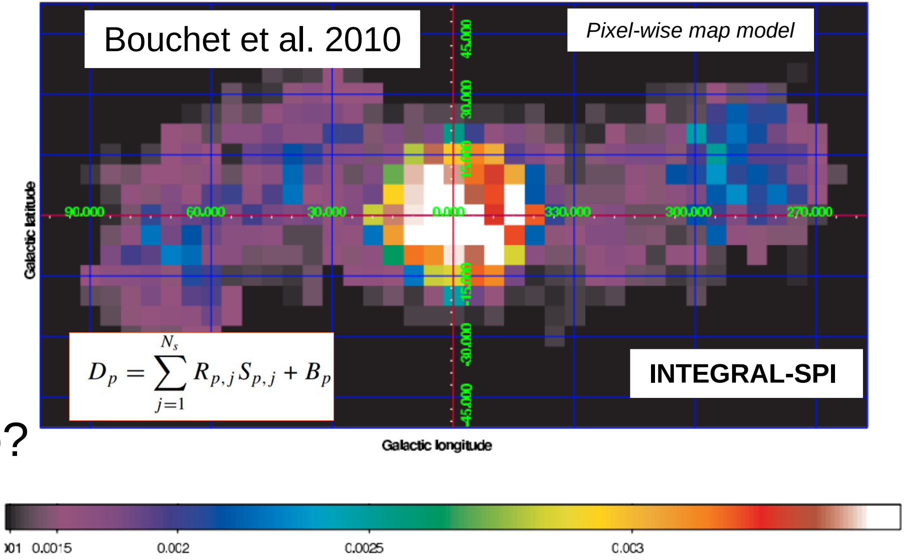
Emission at 511 keV detected since 50 years

Galactic bulge + disk emission detected

Positrons from β^+ decay of ^{26}Al, ^{44}Ti, ^{56}Ni, ^{56}Co?

Disk component: nucleosynthesis from massive stars?

Bulge component: origin not understood
(LM-XRB, NSM, SN-Ia, Sgr A, DM?)



Requirements for future observatories:

- **Constrain shape of emission**
- **Model independent imaging of emission**
- **Sensitivity to large scale galactic halo**
- **Identify correlations with parent isotopes**

The positron annihilation

No excess above 511 keV → No in-flight annihilation
(positrons annihilating at low energies)

Dominant component: positronium annihilation
(inferred from excess at low energy → ortho-positronium)

Fit with narrow+broad line components
(e^+ and para-positronium annihilation)

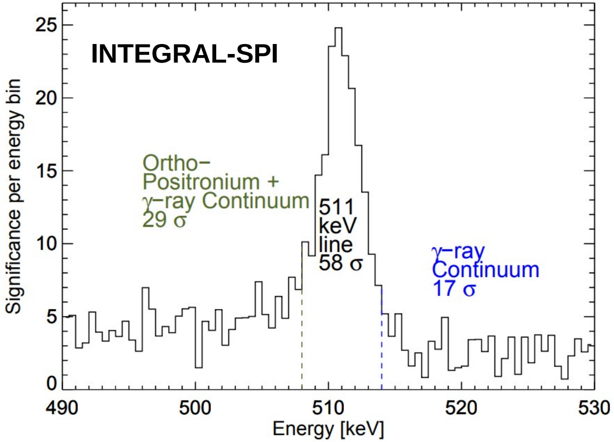
Bulge emission in warm ISM

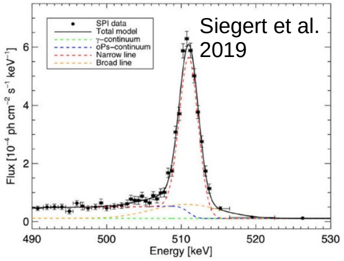
Line shape → Constrain β^+ propagation

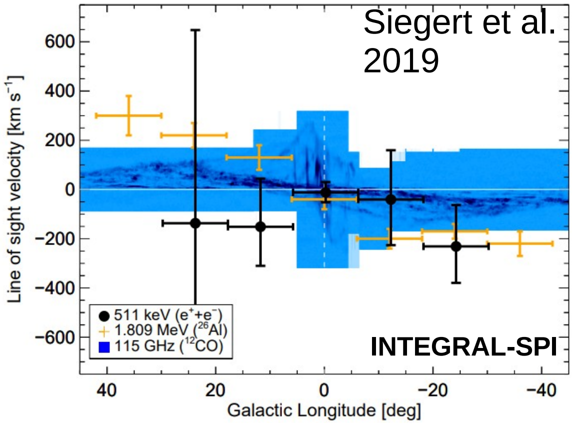
Requirements for future observatories:

- **Resolve spectrum in specific sky regions**
- **Good sensitivity to line shape**

Siegert et al. 2016







The galactic nucleo-synthesis - ^{26}Al

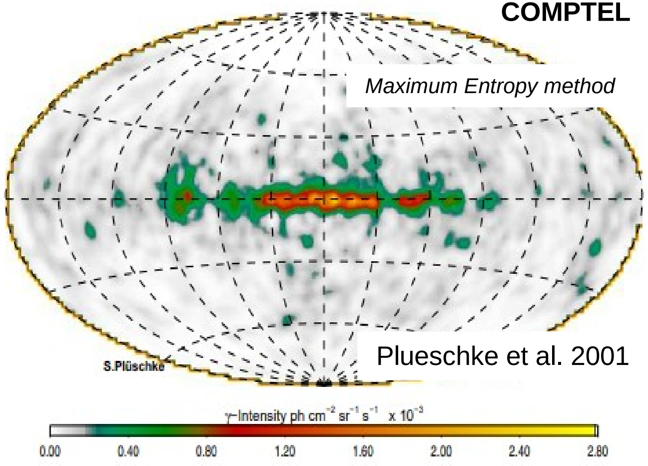
Diffuse emission of ^{26}Al detected both by COMPTEL and INTEGRAL
- 1809 keV
- Decay time ~1Myr

Distributed along the central galactic plane

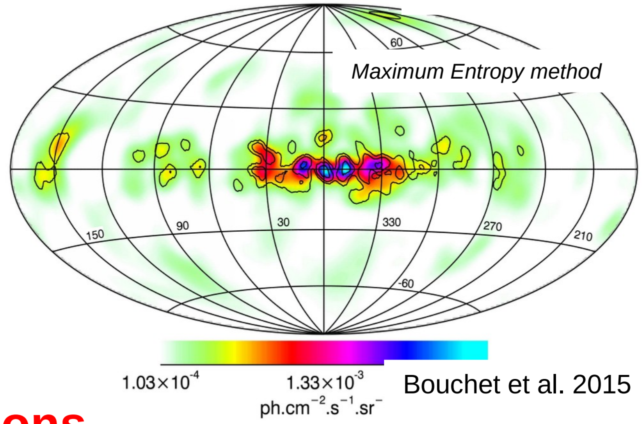
^{26}Al injected in ISM by massive star winds and Core-Collapse Supernovae

Possible hot-spots detected
(Cygnus region and Vela SNR)

Requirements for future observatories:
- **Improve the ^{26}Al spatial resolution**
- **Look for correlations with astronomical populations**



Plueschke et al. 2001



Bouchet et al. 2015

The galactic nucleo-synthesis - ^{60}Fe

^{60}Fe decay chain emission detected by INTEGRAL and COMPTEL

- 1173 and 1333 keV ($^{60}Fe \rightarrow {}^{60}Co \rightarrow {}^{60}Ni$)
- Decay time 2.2 Myr

Too faint signal: no imaging achieved so far

^{60}Fe injected mostly at Core Collapse SN

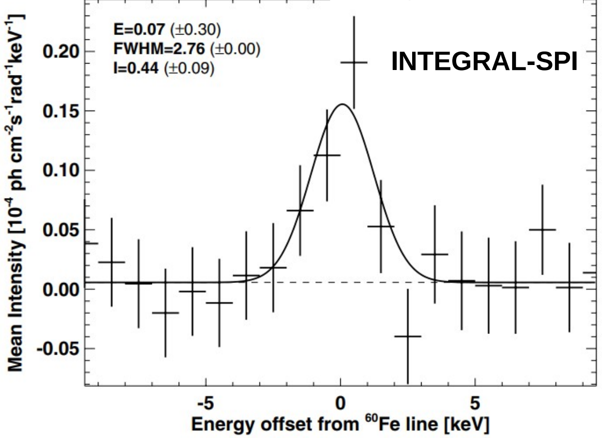
Ratio I(^{60}Fe)/I(^{26}Al) as a test parameter for stellar evolution

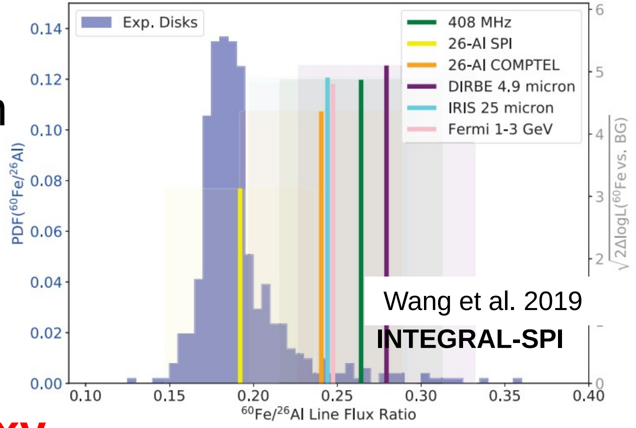
- Constrain the production mechanisms
- Test evolutionary stage of production environments

Requirements for future observatories:

- **Resolve the ^{60}Fe spatial distribution**
- **Measure $^{60}Fe/^{26}Al$ in different locations of the galaxy**

Wang et al. 2007





Wang et al. 2019
INTEGRAL-SPI

The galactic nucleo-synthesis - ^{44}Ti

^{44}Ti emission chain detected by COMPTEL and INTEGRAL

- 1157 keV ($^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$)
- Decay time ~86 yr

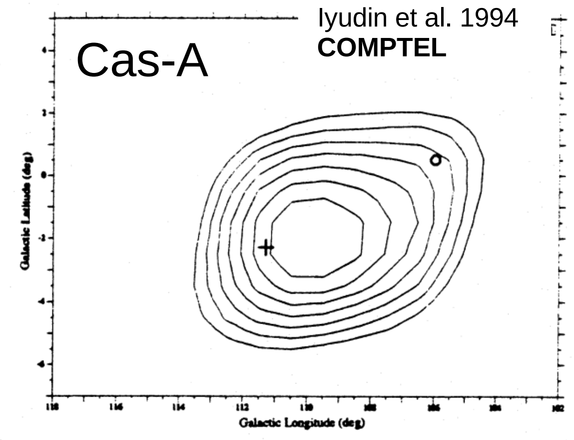
Point-like sources rather than diffuse emission (2 SNR detected: Cas-A and SN1987A)

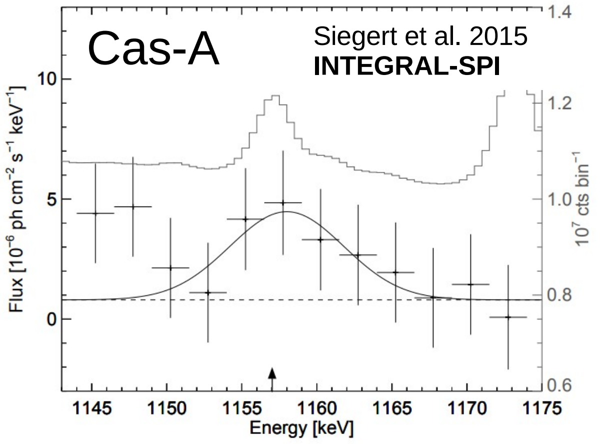
Produced in CCSN (but also SN-1a)

Production mechanisms not well constrained
(too few sources detected+^{44}Ca prediction to be matched)

Requirements for future observatories:

- **Increase the sample of young SNR to constrain ^{44}Ti production mechanisms**





The polarization measurements

Few polarized sources are detected in the COSI energy range:

- Crab pulsar
- Cygnus X1

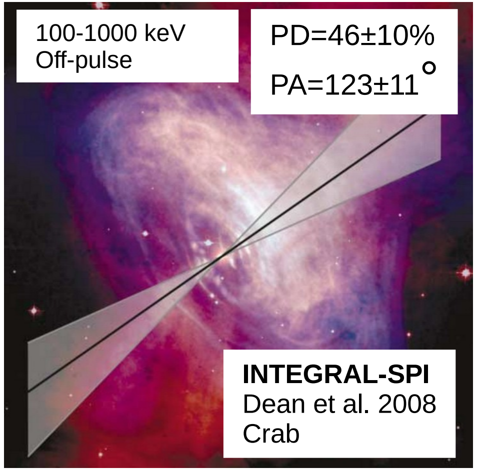
Polarization measured in many sources by IXPE (2-8 keV)

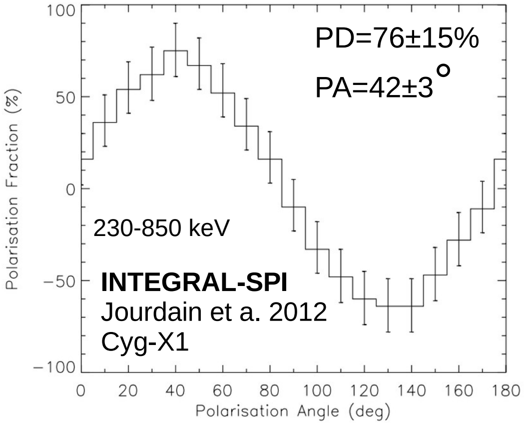
Polarization as a tool to determine source geometry

Discriminate between hadronic and leptonic models by measuring polarization in jets from Blazars

Study emission in AGNs and BHs (SSC vs. IC)

Possibly expand the sample of GRBs and galactic black holes with polarization to characterize their properties





Multimessenger campaigns

The detection of Neutron Star Merger GW170817 opened the way for multi-messenger campaigns

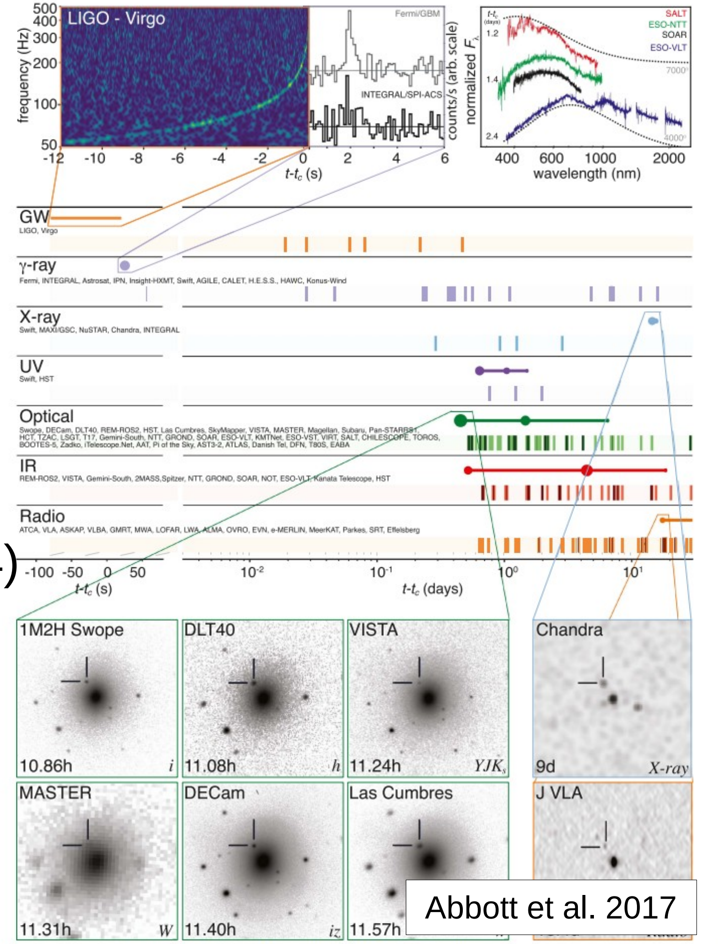
Extensive MM campaigns presently ongoing GW+ν+γ

Ongoing developments:

- LIGO, Virgo, KAGRA concluding Observation Run 4 (O5 scheduled for mid 2027)
- Upgrade of Ice Cube ongoing (Completion in 2024)
- Hyper-Kamiokande due to start in 2027

Requirement for future observatories:

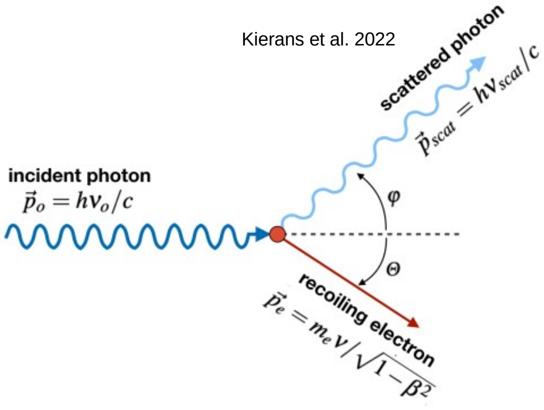
- **Wide field of view imager**
- **High sensitivity, high resolution instrument**
- **Short reporting times**
- **Short reaction time to external alerts**



Abbott et al. 2017

The Compton telescopes

Kierans et al. 2022



Main process: sequence of Compton scatterings

Measured parameters:

- ✓ Recoil electron energy
- ✓ Interaction position
- ✓ Timing of single interaction
- ✓ Direction of electron

Single photon → direction constrained within a circle of opening angle φ

Sum of energy deposits → Energy of primary photon

Sensitivity to polarization

$$\cos(\varphi) = 1 - m_e c^2 \left(\frac{1}{E_{scat}} - \frac{1}{E_0}\right)$$

Scattering angle

Primary energy

Scattered photon energy

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E_{scat}}{E_0}\right)^2 \left(\frac{E_{scat}}{E_0} + \frac{E_0}{E_{scat}} - 2\sin^2(\varphi)\cos^2(\eta)\right)$$

Azimuthal scattering angle

Imaging with Compton telescopes

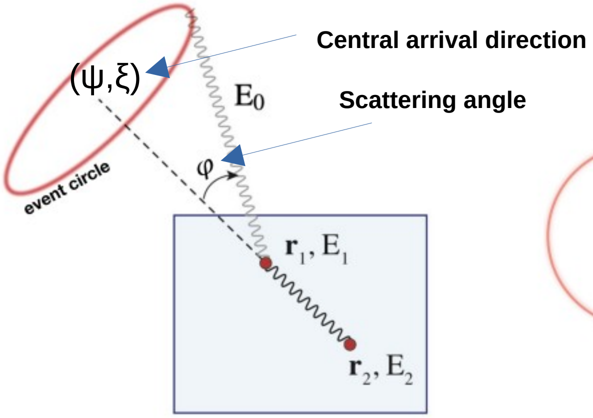
Single photon: arrival direction constrained within a circle

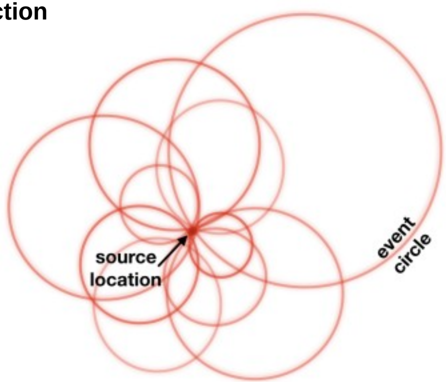
Multiple photons: circle intersection to source location

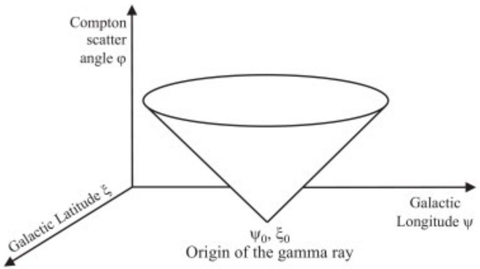
Deconvolution procedure for imaging:

- Richardson-Lucy
- Maximum Likelihood
- Maximum Entropy
- Multi-resolution Regularized
- Expectation
- Model fitting

Response matrix needed to perform the deconvolution







Compton cone
(ψ,ξ,φ)

Equivalent of point spread function in Compton detectors

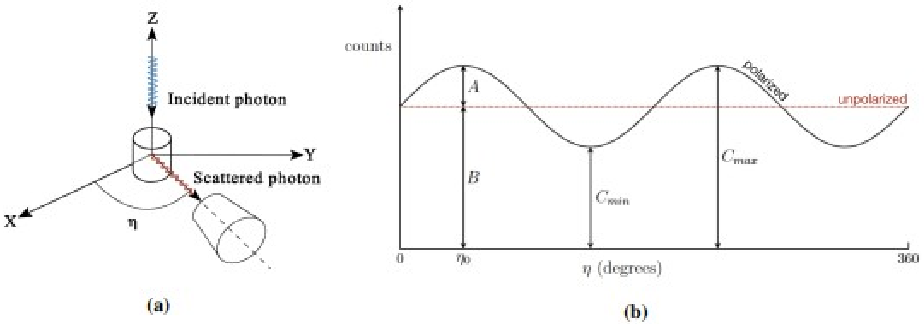
Polarization with Compton telescopes

Modulation in the azimuthal distribution of the Compton scattering

Maximal amplitude for:
- $\varphi=90°$
- $\eta=90°$ (perpendicular to initial photon polarization)
- Low primary energies

Fit cosine modulation along azimuthal distribution (Correcting for spurious modulation)

Maximum likelihood fit to measure polarization



$$\frac{d\sigma}{d\Omega}=\frac{r_0^2}{2}\left(\frac{E_{scat}}{E_0}\right)^2\left(\frac{E_{scat}}{E_0}+\frac{E_0}{E_{scat}}-2\sin^2(\varphi)\cos^2(\eta)\right)$$

Probability Density Function for photon distribution along the azimuthal direction

$$p(\eta)=P_0+A\cos(2(\eta-\eta_0))$$

The COSI mission

Small Explorer NASA mission with a planned launch in 2027

Scientific objectives:

- Study of the galactic positron annihilation
- Study of the galactic element formation
- Study of the polarization at ~MeV
- Participation to multimessenger campaigns

Germanium detectors to achieve excellent energy resolution

Compton telescope sensitive in the 0.2-5 MeV region

Imaging capabilities over 120° field of view

Sensitivity to polarization


Credit: Image by Jim Willis, courtesy of Northrop Grumman Corporation ½ Space Systems; background image courtesy of European Southern Observatory

The COSI collaboration

University of California
- John Tomsick (Principal Investigator, UCB)
- Steven Boggs (Deputy PI, UCSD)
- Andreas Zoglauer (Project Scientist, UCB)

Naval Research Laboratory
- Eric Wulf (Electronics and BGO shield lead)

Goddard Space Flight Center
- Albert Shih (Cryostat Heat Removal Subsystem lead)
- Carolyn Kierans (Data pipeline co-lead)

Space Dynamics Laboratory

Northrop Grumman

UC San Diego

U.S. NAVAL RESEARCH LABORATORY

NASA

ASI Agenzia Spaziale Italiana

NORTHROP GRUMMAN

COSI

Institutions of Co-Investigators and Collaborators
- Clemson University
- Louisiana State University
- Los Alamos National Laboratory
- Lawrence Berkeley National Laboratory
- IRAP, France
- INAF and ASI, Italy
- Kavli IPMU and Nagoya University, Japan
- JMU/Wuerzburg and JGU/Mainz, Germany
- NTHU, Taiwan
- University of Hertfordshire, UK
- Centre for Space Research, North-West University, South Africa
- Deutsches Elektronen Synchrotron (DESY), Germany
- LAPTh-CNRS, France
- Yale University
- Michigan Technical University
- Washington University, St. Louis
- Marshall Space Flight Center
- Boston University
- IAA-CSIC, Spain
- Stanford University

The COSI mission profile

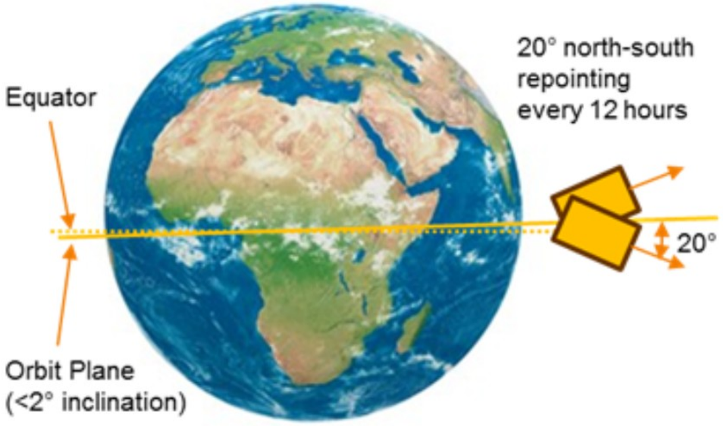
2-year mission

To reduce background contamination:
- Equatorial orbit (inclination < 2°)
- Quasi-circular orbit
- 550 km altitude

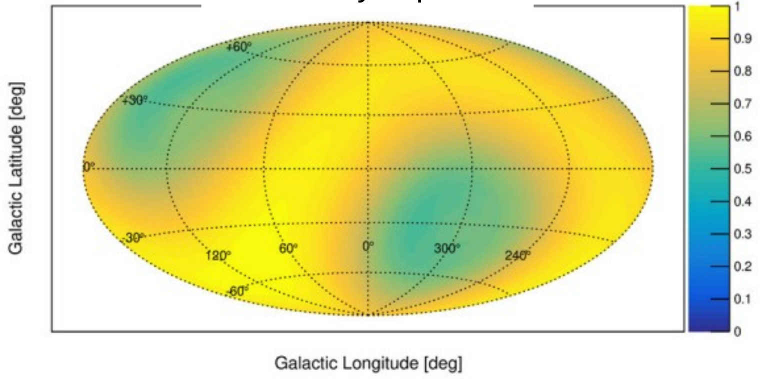
12 hours ±20° zenith pointing cycles
- Full sky exposure every day

Possibility to operate in Target Of Opportunity mode using the Constant Zenith Angle mode (CZA)

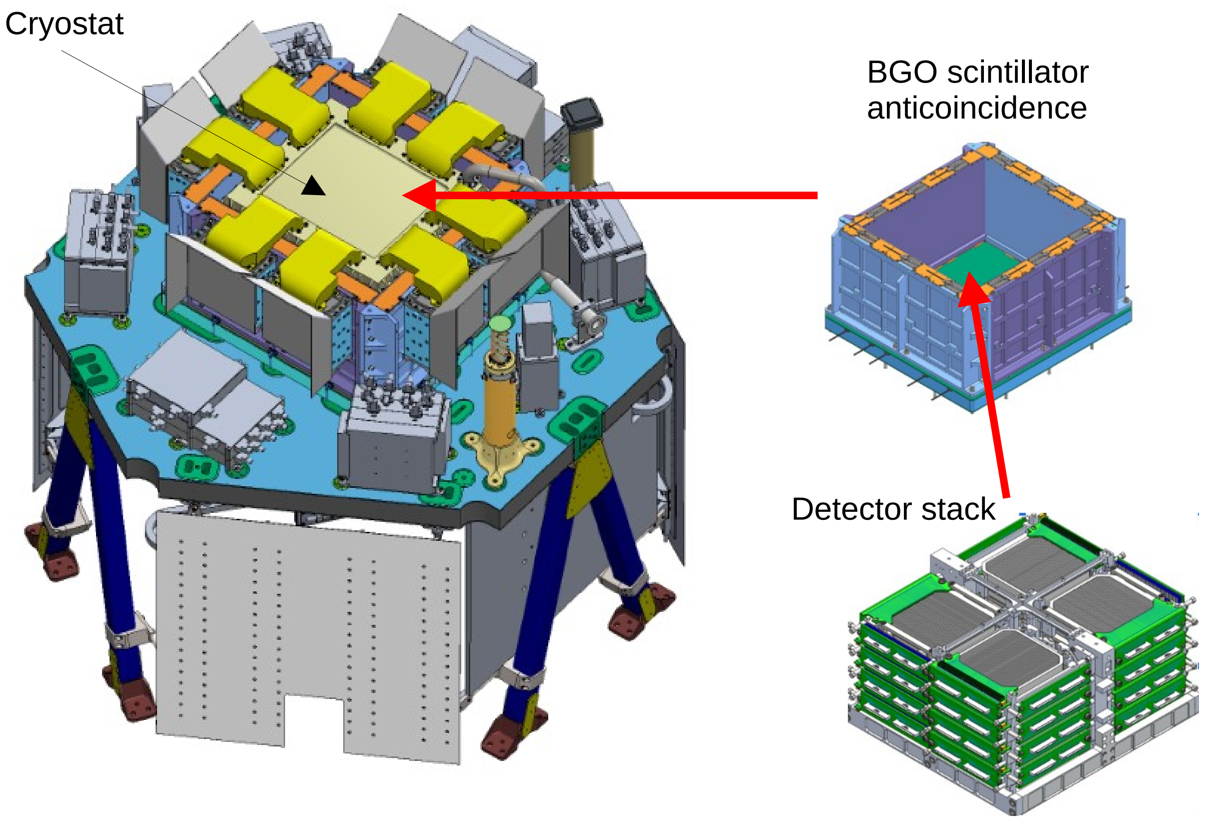
For calibration: inertial pointings to the Crab nebula (12 hours duration)



COSI daily exposure



The Compton Spectrometer and Imager



3D array of ultrapure Germanium detectors

Detector @85K in cryostat

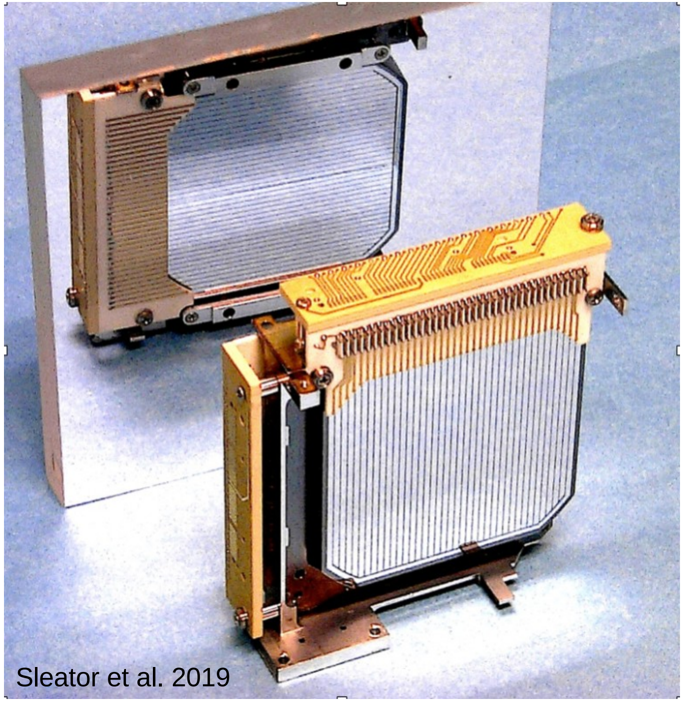
Stack of 4 layers

2x2 detectors in each layer

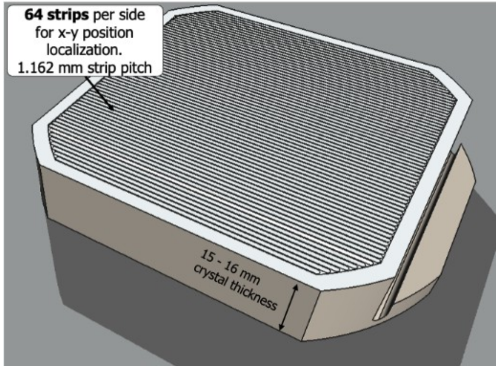
Detector size: 74x74x15mm

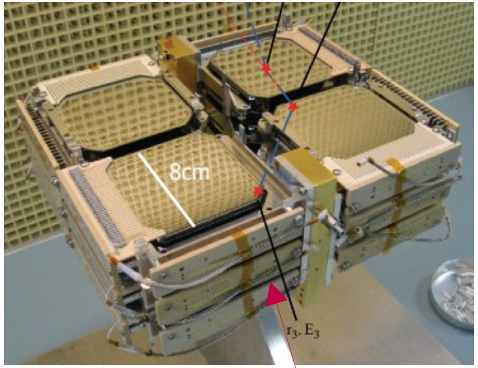
Bismuth Germanium Oxide scintillators for shielding
- Read out with SiPMs
- Shielding on 5 sides

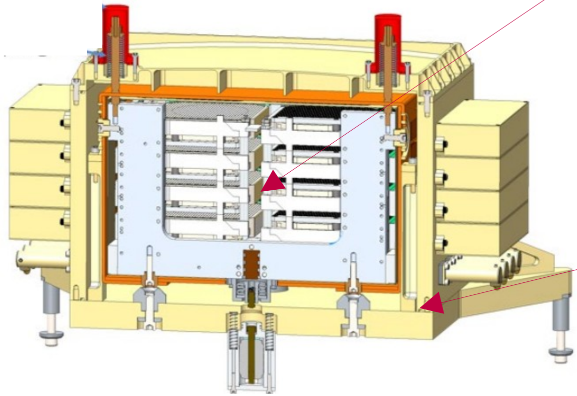
The detectors



The cross-strip Germanium detector







COSI requirements

Parameter	Requirement
Sky coverage	25% instantaneous view of the sky Full sky on single day
Spectral resolution* *For fully reconstructed Compton events	6 keV @ 511 keV 9 keV @1809 keV
Angular resolution	4.1° @ 511 keV 2.1° @ 1809 keV
Line sensitivity	1.2×10^{-5} photons cm^{-2} s^{-1} @ 511 keV 3×10^{-6} photons cm^{-2} s^{-1} @ 1809 keV
Flux limit for polarization	1.4×10^{-10} erg cm^{-2} s^{-1} (0.2-0.5) MeV
Report short GRB detection	< 1 hour reporting time <2.5° localization (90% CL radius) 100 ms absolute time accuracy

The COSI event reconstruction

Several methods to reconstruct the event

Sequence of Compton interactions to be reconstructed

Small detector → Interactions not ordered in time

High density, moderate-Z detector → No e^- recoil trace

Only available information:

- Position of the interaction (~mm scale)
- Energy deposit (few keV resolution)

Test interaction order with constraints:

- Compton formula
- Cross section formulas

Approach 1

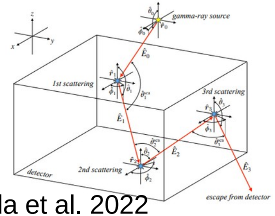
$$\cos^{Compt}(\varphi)=1-m_e c^2\left(\frac{1}{E_{scat}}-\frac{1}{E_0}\right)$$

$$\cos(\varphi_l^{Geo})=\frac{\vec{g}_k\cdot\vec{g}_l}{|g_k||g_l|}$$

$$\chi^2=\frac{\sum_{i=1}^{N-1}\left(\cos(\varphi^{Comt})-\cos(\varphi^{Geo})\right)^2}{(d\cos(\varphi^{Compt}))^2+(d\cos(\varphi^{Geo}))^2}$$

Approach 2

Test different orders maximizing the probability accounting for the physics of each interaction

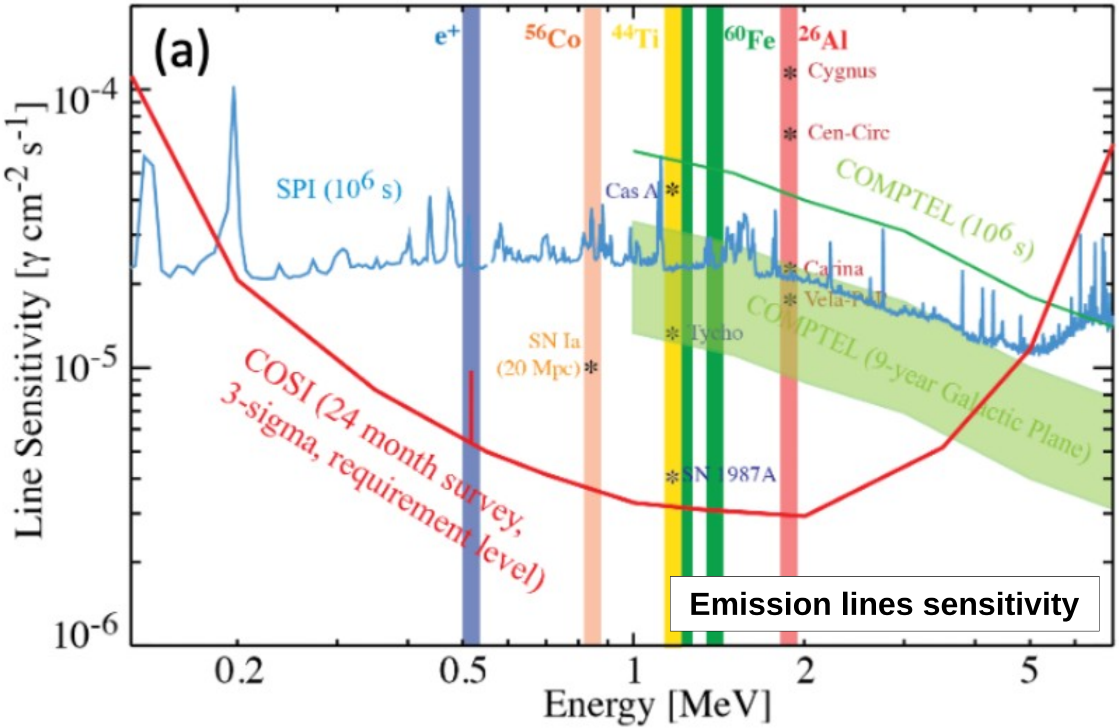


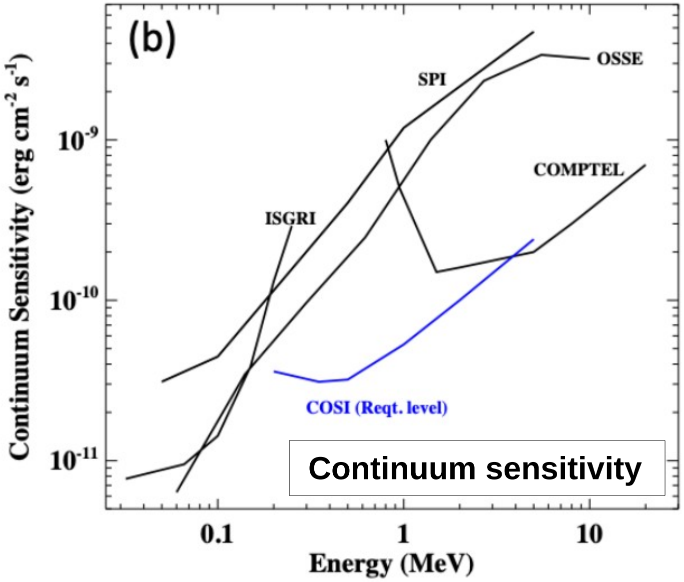
Yoneda et al. 2022

Approach 3,4...

Bayesian method
NN method
...

The required COSI sensitivity curves

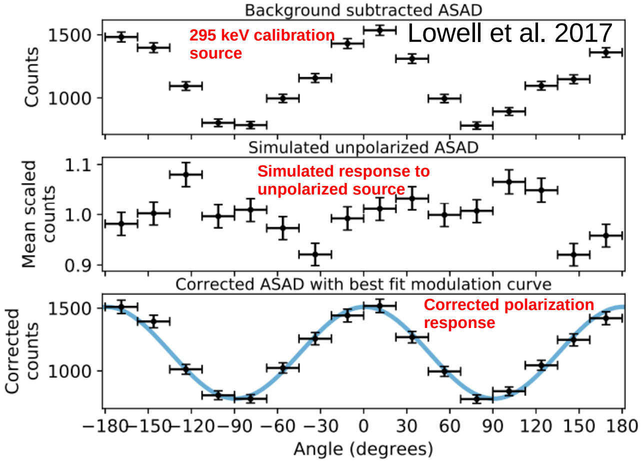




Up to factor 4-5 in the sensitivity for continuum

Factor 4-10 improvement in the sensitivity for main emission lines

The COSI performance – polarization



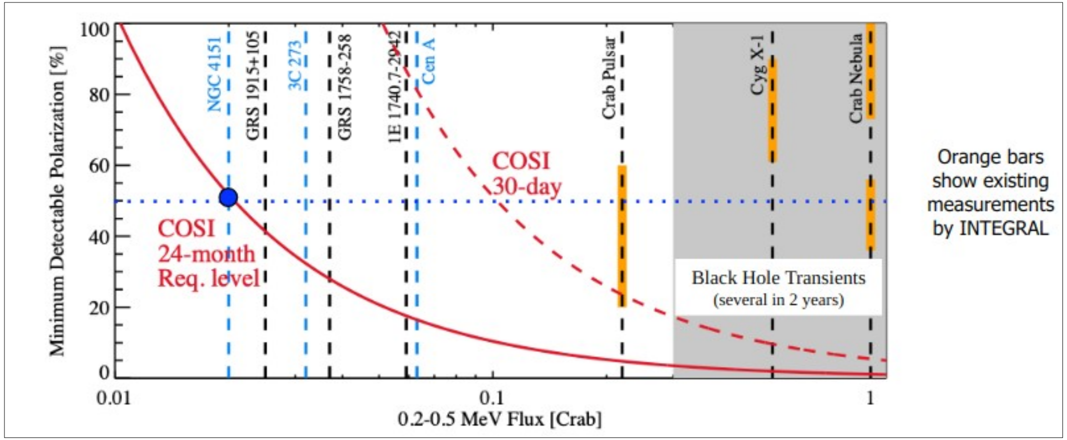
COSI will open the polarization window in the MeV region (from few examples to small statistics)

~30 GRB expected with Minimum Detectable Polarization of 50% in 2 years

~10 GRBs with 5-10% polarization detection

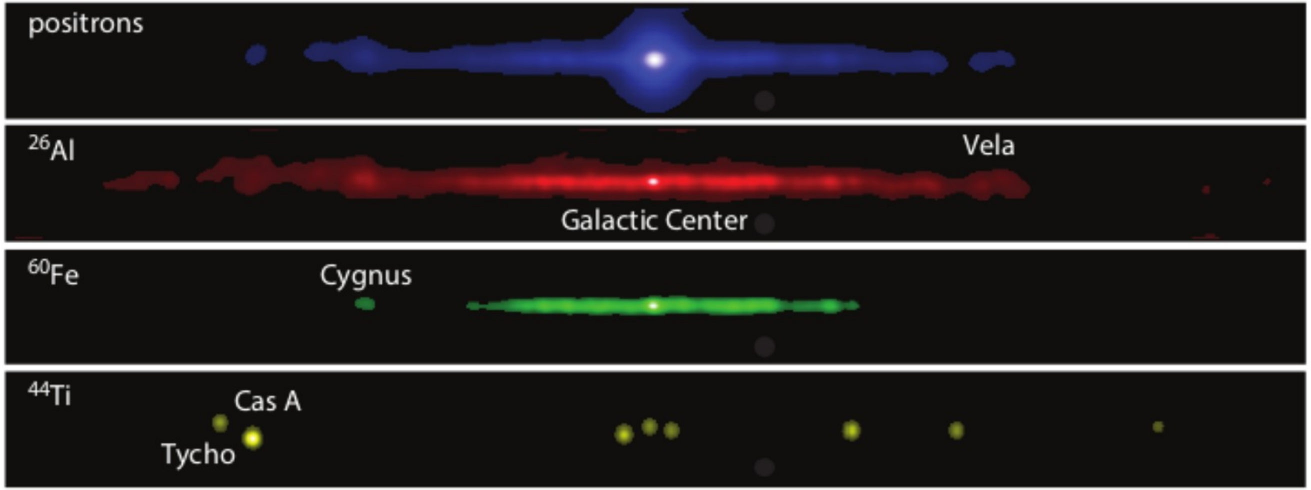
For continuous sources: 20 mCrab in the 0.2-0.5MeV range:

- 3 AGNs required
- 3 galactic black holes sources required



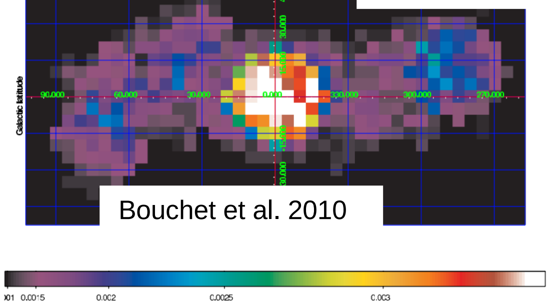
Orange bars show existing measurements by INTEGRAL

The simulated COSI sky



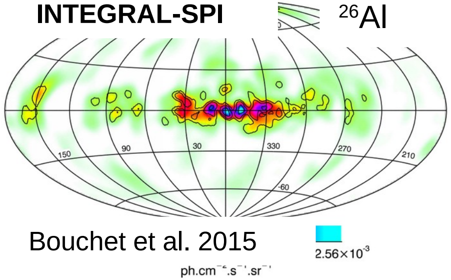
COSI will significantly improve the knowledge of the gamma ray sky

INTEGRAL-SPI Positrons



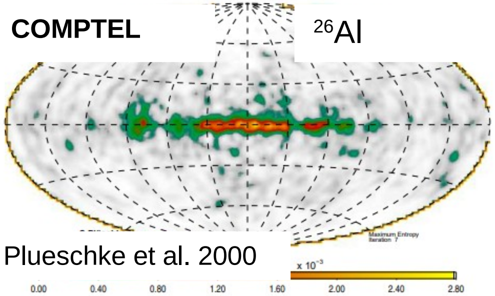
Bouchet et al. 2010

INTEGRAL-SPI ^{26}Al



Bouchet et al. 2015

COMPTEL ^{26}Al



Plueschke et al. 2000

INTEGRAL-SPI & COMPTEL

Iron detected but not imaged

Titanium detected in few sources

Summary

Several open issues in the gamma ray field addressed with COSI

- Origin of the 511 keV emission line
- Stydy of galactic nucleosynthesis
- Open the polarization window in the ~MeV region
- Contribute to multi messenger campaigns

Despite the challenging task, COSI is expected to improve the sensitivity in the ~MeV region by a factor of almost 10

Good energy resolution (0.5-1%)

Good angular resolution (2-4°)

Polarization sensitivity in the MeV region

Thank you for your attention

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